Color-Octet Contribution to J/ψ Hadroproduction with Nonzero p_T at Fixed Target Energies

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Abstract

We calculated the color-octet contribution to the J/ψ hadroproduction at fixed target energies $\sqrt{(s)} \simeq 40$ GeV. We consider the J/ψ production with transverse momenta which can not be explained by primordial motion of partons, $p_T > 1.5$ GeV. It is shown that color octet contribution is dominant at these energies and reduces large dicrepancies between experimental data and color singlet model predictions. Having taken into account both contribution one needs a K-factor about 2-3 to explain the experimental data.

Investigation of the processes of heavy quorkonia production gives an excellent possibility to study a perturbative feature of QCD and allows one to extract long-distanse effects connected with hadronization phaze. Due to the large mass of c and b quarks production of the heavy quark-antiquark pair takes place at the short distances ($\sim m_Q$) and can be controled within the framework of perturbative QCD (PQCD). Then, the quark pair is bound into a quarkonium in a time scale of order of the the inverse binding energy, $\tau \simeq 1/(m_Q v^2)$, where v is the velocity of quarks within the bound state. As $m_Q \rightarrow \infty$, the heavy quark velocity inside the bound state $v \sim 1/ln(m_q) \rightarrow 0$, and above mentioned two time scales become widely separated $m_Q > m_Q v^2$ (for $b\bar{b}$-system $v^2 \simeq 0.08$ and for $c\bar{c} - v^2 \simeq 0.23 - 0.3$, charmonium is not truly nonrelativistic system). The separation of time scales makes possible to factorize production process of a heavy quarkonium in the short distance and long distance parts. Short distance part describes the heavy quark-antiquark pair production and can be controled perturbatively.

The long distance part is related to matrix element responsible for the hadron formation from the quark-antiquark pair.

Quarkonium production has traditionally been calculated in the color singlet model (CSM) [1]. In this approach is proposed that quark-antiquark pair is produced in a color singlet state with the quantum numbers of the corresponding hadron. This heavy pairs eventually creates the hadronic state with a probability determined by the appropriate quarkonium wave function at the origin. It is assumed that for heavy quarks soft gluon emmision as well as other nonperturbative effects such as higher twist contributions are negligible. While this model gives a reasonable description of J/ψ production cross section shape over p_T or x_F it completely fails in the explanation of the integrated cross cross section (K factor 7-10 is needed to explain experimental data). The anomalously large cross section [2] of J/ψ production at large transverse momenta at the Tevatron reveals another bad feature of the CSM. Within the framework of the CSM it is impossible to explain the anomalously large ψ [3] and direct J/ψ production [4] at CDF experiment.

Indeed, the requirements of the CSM is very strong and lead to the suppression of both fusion and fragmentation contributions. Production of a quark-antiquark pair on the time scale $\tau \simeq 1/m_Q$ with the proper quantum numbers of subsequent hadronic state must be accompanied with the emmition of hard gluons. Therefore, production cross section in the CSM is suppressed by powers of α_s/π.

The CSM is a nonrelativistic model where the relative velocity between the heavy constituents in the bound state is neglected. But discrepancies between experimental data and CSM predictions hint that $O(v)$ corrections as well as other mechanisms of quarkonia production, which do not appear at leading order in v, should be considered. Treating higher order in v it is possible to avoid the supression caused by emission of hard gluons, if one allows a quark-antiquark pair to be produced on the time scale $1/m_Q$ in any color state (singlet or octet) with any quantum numbers. Such a pair evolves into a hadron state by emitting of soft gluons with momenta of an order of

$m_Q v^2$. Expansion of quarkonium cross sections and decay widths in the powers of relative velocity v of heavy quarks in a bound state has recently been realized in terms of Nonrelativistic QCD (NRQCD) [5]. This formalism implies not only color-singlet processes but so called color-octet mechanism, when a quark-antiquark pair is produced on the small time scales in the color octet state and evolves into hadron by emmition of soft gluons. According to the factorization approach based on the NRQCD, the production cross section for quarkonium state H in the process

$$A + B \rightarrow H + X \tag{1}$$

can be written as

$$\sigma_{ij} = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{j/B}(x_2) \hat{\sigma}(ij \rightarrow H) \tag{2}$$

$$\hat{\sigma}(ij \rightarrow H) = \sum_n C^{ij}[n] < 0|O^H[n]|0 >$$

where the $f_{i/A}$ is the distribution function of the parton i in the hadron A. Sub-prosess cross section is separeted into two: short distance, $C^{ij}[n]$, and long distance, $< 0|O^H[n]|0 >$, parts. The $C^{ij}[n]$ is the production cross section of a heavy quark-antiquark pair in the i and j parton fusion. It should be calculated in the framework of PQCD. The [n] state can be either a color singlet or octet state. The $< 0|O^H[n]|0 >$ describes evolution of a quark-antiquark pair into a hadronic state. These matrix elements cannot be computed perturbatively. But relative importance of long distance matrix elements in powers of velocity v can be estimated by using the NRQCD velocity scaling rules [6].

The shapes of the p_T distribution of short distance matrix elements within the color octet model indicates that new mechanism can explain the Tevatron data of direct J/ψ and ψ production at large p_T. But unlike color-singlet matrix elements connected to the subsequent hadronic nonrelativistic wave functions at the origin, the color octet long distance matrix elements are unknown and should be extracted from experimental data. Explanation of the CDF data of S state charmonia production at the large p_T will be succesfull after testing the values of color octet long distance matrix elements in other experimental data

The color octet contribution to the J/ψ photoproduction was analized in the papers [7, 8]. Recently, the J/ψ hadroproduction at fixed target energies has been studied by including color-octet mechanism [9, 10]. Large discrepancies between experimental data and CSM predictions for the J/ψ production total cross section were explained. The color octet contribution is dominant in the J/ψ hadroproduction at energies $\sqrt{(s)} \simeq 30 - 60$ GeV. The analises carried out in these papers [7, 8, 9, 10] demonstrate that to fit the photoproduction and hadroproduction data at the low energies require rather small values for color octet matrix elements than those extracted from a prompt J/ψ production at CDF [12].

In the present letter we consider the color octet contribution to the J/ψ hadroproduction with nonzero p_T at fixed target energies. We called nonzero p_T such transverse momenta which cannot be explained by primordial motion of partons inside the colliding hadrons. We consider $p_T > 1.5$ GeV to calculate the short distance matrix elements perturbatively and avoid the infrared and collinear divergencies in the production of $^1S_0$ and $^3P_{0,2}$ quark-antiquark states.

In the papers [9, 10] for calculation of the total cross section of the J/ψ production only the subprocesses $2 \rightarrow 1$ were taken into account. These subprocesses are the lowest order in perturbative series over α_s and give the main contribution to the integrated cross section. The transverse momenta of produced particles due to internal motion of partons are of an order Λ_{QCD}, and p_T behaviour of the cross section cannot be controlled perturbative. The subprosses $2 \rightarrow 2$ are the lowest order which contribute to the J/ψ production at $p_T >> \Lambda_Q CD$.

$$gg \rightarrow (c\bar{c})g,$$
$$gq \rightarrow (c\bar{c})q, \qquad (3)$$
$$qq \rightarrow (c\bar{c})g,$$

where $(c\bar{c})$ denotes any state of heavy quark-antiquark pair. These subprocesses give small contribution to the total cross section because additional α_s and the steeply falling down p_T behaviour. The cross section of the J/ψ production can be written as

$$\sigma_{J/\psi} = \sigma(J/\psi)_{dir} + \sum_{J=0,1,2} Br(\chi_{cJ} \rightarrow J/\psi X)\sigma_{\chi_{cJ}} + Br(\psi' \rightarrow J/\psi X)\sigma_{\psi'}, \qquad (4)$$

where in the production of each quarkonium state is contributed by both color singlet and octet states,

$$\sigma(J/\psi)_{dir} = \sigma_{J/\psi}^0 + \sigma_{J/\psi}^8 + \sum \sigma(Q\bar{Q}(^{2s+1}P_J^{(8)}) < 0|O_8^{J/\psi}(^{2s+1}L_J|0 > \qquad (5)$$

where the sum stands over the states $^3P_{0,1,2}^8$, $^1S_0^8$ and $^3S_1^8$. The expressions for differential cross sections for color singlet states we take from [1, 11]. For color octet states the short distance matrix elements have recently been calculated by Cho and Leibovich [12].

As concerned the long distance matrix elements their number should be reduced by using NRQCD spin symmetry relations:

$$< 0|O_8^H(^3P_J)|0 >= (2J+1) < 0|O_8^H(^3P_0)|0 >, \qquad (6)$$
$$< 0|O_8^{\chi_{cJ}}(^3S_1)|0 >= (2J+1) < 0|O_8^{\chi_{c0}}(^3S_1)|0 > . \qquad (7)$$

After that from the parameters which give main contribution in the cross section only four independent matrix elements remain; $< 0|O_8^{J/\psi}(^3S_1)|0 >$, $< 0|O_8^{\chi_{c1}}(^3S_1)|0 >$, $< 0|O_8^{J/\psi}(^3P_0)|0 >$ and $< 0|O_8^{J/\psi}(^1S_0)|0 >$. Unfortunatly, values for these matrix

elements obtained from fitting various experimental data are different. There are two different values for the matrix elements $< 0|O_8^{J/\psi}(^3S_1)|0 >$, $< 0|O_8^{\chi_{c1}}(^3S_1)|0 >$, extracted from CDF data by two group of authors. Using only the dominant fragmentation contributions to the J/ψ production Caciari et al.[4] obtained the following values:

$$< 0|O_8^{J/\psi}(^3S_1)|0 >= 15 \cdot 10^{-3} GeV^3,$$
$$< 0|O_8^{\chi_{c1}}(^3S_1)|0 >= 2.4 \cdot 10^{-2} GeV^3.$$

Using the full perturbative expressions for the short distance matrix elements Cho and Leibovich obtained smaller values by factor two for the above parameters, $6.6 \cdot 10^{-3} GeV^3$ and $9.8 \cdot 10^{-3} GeV^3$, respectively.

As for the other two parameters it is possible to extract only their combinations from experimental data. From charmonium production at large transverse momenta at CDF Cho and Leibovich extracted [12]

$$< 0|O_8^{J/\psi}(^1S_0)|0 > +\frac{3}{m_c^2} < 0|O_8^{J/\psi}(^3P_0)|0 >= 6.6 \cdot 10^{-2} GeV^3. \tag{8}$$

Different combination of these parameters were extracted from J/ψ photoproduction data and hadroprodaction data at fixed target energies:

$$< 0|O_8^{J/\psi}(^1S_0)|0 > +\frac{7}{m_c^2} < 0|O_8^{J/\psi}(^3P_0)|0 >= 2 \cdot 10^{-2} GeV^3 [10],$$
$$< 0|O_8^{J/\psi}(^1S_0)|0 > +\frac{7}{m_c^2} < 0|O_8^{J/\psi}(^3P_0)|0 >= 3 \cdot 10^{-2} GeV^3 [7,\ 8]. \tag{9}$$

As one can see from equations (8) and (9) the photoproduction and hadroproduction data at low energies are consistent with each other within the model error. But there is the large discrepancy between the low, (9), and high energy, (8), values of the parameters. Solving the system of equations (8) and (9), one will obtain a negative value for the $< O_8^{J/\psi}(^3P_0) >$ matrix element. The reason for such discrepancy may be an overestimation of the value obtained in the paper [12] (equation 8). In the prompt J/ψ production at the Tevatron the $^1S_0^{(8)}$ and $^3P_J^{(8)}$ states give a dominant contribution at transverse momenta near $p_T = 5$ GeV. The value $6.6 \cdot 10^{-2} GeV^3$ was extracted just from this region of p_T. But at these values of transverse momenta J/ψ is produced mainly at small partonic x ($x \sim 10^{-2} \div 10^{-3}$) in the gluon-gluon fusion. Cho and Leibovich in paper [12] use the partonic parametrization MRSD0 [14]. But in the above mentioned region of x the MRSD0 parametrization gives rather smaller value for the gluon distribution function than more realistic parametrization (GRV LO or GRV HO [15]). Using GRV LO parametrization gives 1.55 times large values for the production cross sections of $^1S_0$ and ^3P_J states. So, more realistic value for the combination (8) is

$$< 0|O_8^{J/\psi}(^1S_0)|0 > +\frac{3}{m_c^2} < 0|O_8^{J/\psi}(^3P_0)|0 >= 4 \div 4.4 \cdot 10^{-2} GeV^3. \tag{10}$$

Consequently, value of $1.4 \div 1.5$ times large is needed for the $< O_8^{J/\psi}(^3S_1) >$ matrix element to explain the prompt J/ψ production cross section at $p_T \simeq 10$ GeV [12],

$$< O_8^{J/\psi}(^3S_1) >= 9 \div 10 \cdot 10^{-3} GeV^3. \tag{11}$$

After these changes the dicrepancy between the combinations (9) and (10) would not be large for the radical choice $< O_8^{J/\psi}(^3P_0) >= 0$.

We presented here, fig.1, results for the differential cross section for the set of parameters taken from [12]. We asumed that $< O_8^{J/\psi}(^1S_0) >=< O_8^{J/\psi}(^3P_0) >$.

In the fig.2 presented the differential cross section for another set of parameters obtained after taking into account above mentioned corrections:

$$
\begin{aligned}
< O_8^{J/\psi}(^3S_1) > &= 10.5 \cdot 10^{-3} GeV^3, \\
< 0|O_8^{\chi_{c1}}(^3S_1)|0 > &= 9.8 \cdot 10^{-3} GeV^3, \\
< O_8^{J/\psi}(^1S_0) > &= 3.7 \cdot 10^{-2} GeV^3, \\
< O_8^{J/\psi}(^3P_0) > &= 0.
\end{aligned}
\tag{12}
$$

For $< O_8^{J/\psi}(^1S_0) >$ we choose the medium value of the combinations (9) and (10). For parameters which describe the transition color octet state into a ψ'-meson we use the values from [12]. Theoretical predictions are compared with the experimental data of experiment E689 at FNAL [13]. We use the functional form of for p_T distribution from [13] to reproduce the curve of experimental data (fig.1,2). As one can see from figures color octet contribution is dominant. But the total theoretical prediction are small and K-factor about $2 \div 2.5$ is needed to explain the experimental data. It is wort to mention that in our calculations there is uncertainty that lead to the decreasing of the theoretical prediction in the whole region of considered p_t. The relative velocity of c and $\bar{c}$ quarks in the charmonium is about $v^2 \simeq 0.23 \div 0.3$. This means that soft gluons emmited from color octet quark-antiquark state while evolution into J/ψ has an momentum about $0.7 \div 1$ GeV ($2m_c v^2$). So, it is necessary to produce color octet state of quark-antoquark pair with mass large then $2m_c$. In the case of the photoproduction or the total cross section in hadroproduction at fixed target energies the kimematical effect from the difference between the mass of J/ψ and color octet quark-antiquark pair is very large [10] since the gluon distribution rises steeply at small x. This reduces cross sections twice and 'true' matrix elements would therefore be large than those extracted by using the small mass of quark-antiquark pair [10]. In our case the influence of such effect is not so large and leads to the decreasing the cross section by about 25% at $p_t \sim 1.5$ GeV and by about 10% at $p_t \sim 3$ GeV. Another uncertainty comes from decay process of quark-antiquark pair into J/ψ. The J/ψ production cross section shape over p_T differs from that of color-octet quark-antiquark pair. For qualitative estimations of this corrections we assumed that produced quark-antiquark state is unpolarized and its decay into

J/ψ and gluon is isotropic. In this approach we calculated the deviation of the J/ψ p_T distribution shape from the distribution shape of heavy quark-antiquark pairs with mass 4 GeV. The difference is negligible near $p_T \sim 1.5$ GeV and at 3 GeV is about 20%. Unfortunately, we can only qualitatively estimate these two corrections because the true mass of a quark-antiquark state before evolution into hadronic state is unknown. But it is obvious that these two corrections lead to the reduction not to the rising of the cross section.

In conclusion, we have calculated the color octet contribution to the J/ψ hadroproduction with nonzero p_T at fixed target energies. Color octet processes are dominant in the J/ψ production and large about an order of magnitude then color singlet contribution.

After taking into account color octet contribution the K-factor about $2 \div 3$ is need to explain the experimental data. Uncontrolled corrections coming from the decay process of quar-antiquark states into J/ψ and 'soft' gluons leads only to the decreasing of the cross section and discrepancies become larger.

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FIGURE CAPTIONS

Fig.1. Transverse momentum diferential cross sections for the set of color octet matrix elements from [12]; solid curve represents experimental data from [13], dashed curve – total theoretical predictions and dotted curve – CSM predictions.

Fig.2. Transverse momentum diferential cross sections for the color octet matrix elements from eq.(12); The curves in this figure are labeled in the same way as in fig.1.
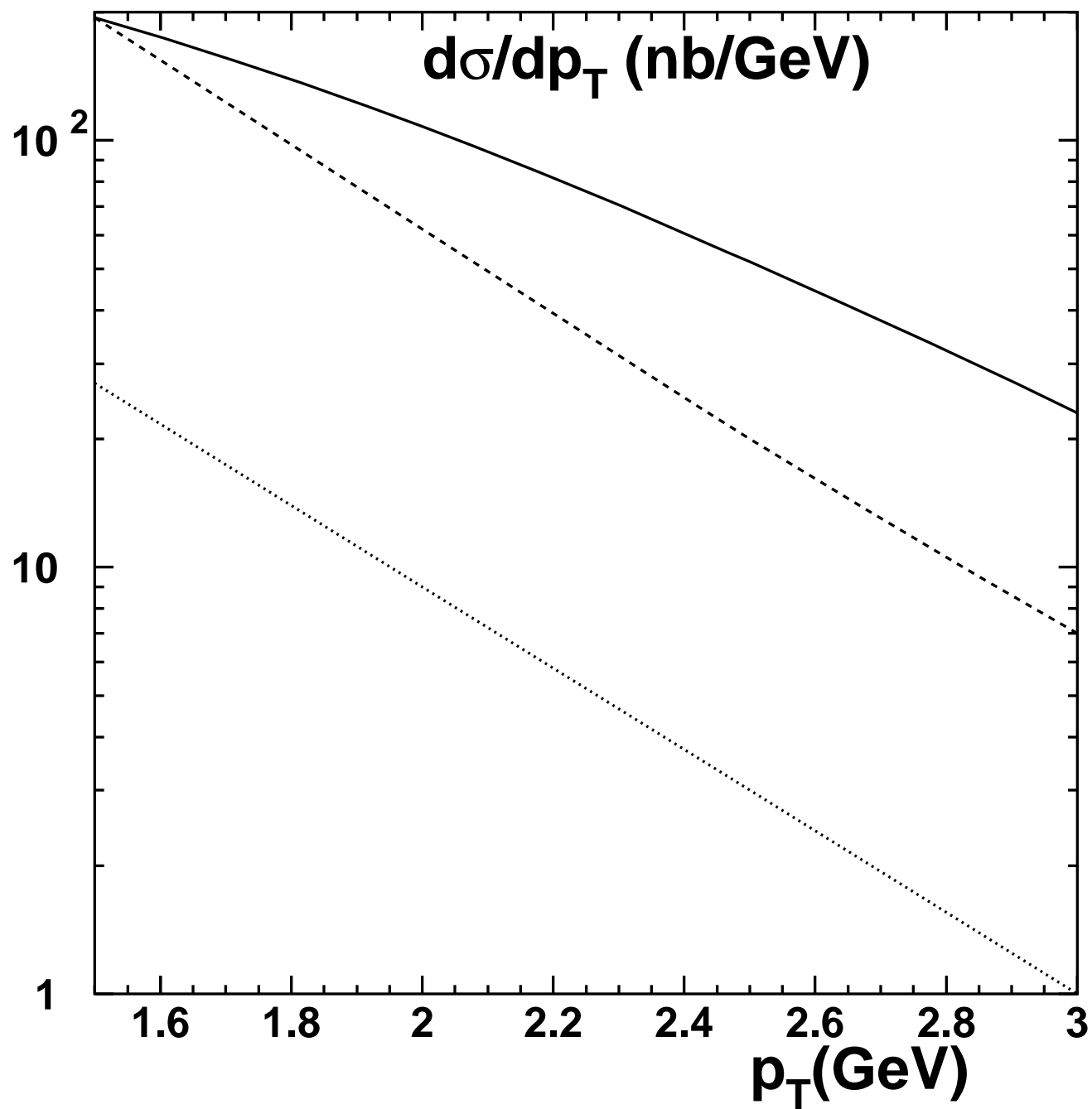
Figure 1

$d\sigma/dp_T$ (nb/GeV)

p_T(GeV)

Figure 2